Models of Manipulators and Manipulation

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Introduction

As a complex and expensive mechanical system, a manipulator, whether commanded by man or computer, is often better studied by and developed from a mathematical model of the system than by direct observation. Furthermore if we can build such a model of a system we have demonstrated our understanding of that system. The better our understanding, the more accurate and simple the model tends to be. This circular process of "understand a system to build a model to understand the system" is a basis, of progress in the natural sciences. In dynamic models of manipulators a fundamental feature is the compliance and mass of the components, Modeled adequately in the most basic sense by Newton's laws of motion and Hooke's law for elastic deformation. Yet the understanding to build simple models, models simple enough to understand, does not exist. More critically the model of how the performance of manipulation is related to the mechanical performance of the manipulator does not exist, not at the basic level of Newton's laws, nor at an empirical level based on more than twenty-five years of direct observation.

The state of the art, its direction, and its preferred direction must be described from an individual's perspective. The perspective here is of one who has been involved for several years in seeking understanding for modeling (MIT Department of Mechanical Engineering [1, 2, 3]) and in building models for understanding (research fellow NASA Johnson Space Center [4] and a current project at the Georgia Institute of Technology to design and build a planar experimental manipulator).

Dynamical Models of Flexible Behavior

The potential variety in mechanical configurations for manipulators requires some qualification of the following remarks. The distinction will be made between "clean" manipulators and "cluttered" manipulators.

Clean manipulators typically consist of distinct power train components and slender beams for skeletal or support functions which are well modeled by Euler or Timoshenko beam equations. They are typified by the Space Shuttle Remote Manipulator system. (They also idealize the cluttered manipulator in general dynamic characteristics.) The manipulators that directly qualify (without idealization) must be "long" compared to the dimensions of the drive train components. Their structural design will be dominated by stiffness rather than strength. The motion of the long arm will result in slower configuration changes than with cluttered arms.

"Cluttered" arms typically have drive train components of such a size that practical design dictates a complicated structural shape, perhaps incorporating drive train housings which double as structural members. The strength requirements on their structure is more severe than for clean arms and there results a less complaint design. Skeletal member compliance is not easily predicted from simple models. Finite elements or measurements are more suited for this task. The more massive drive train results in (or from) more rapid motion, at least compared to arm length, and more rapid configuration change results. The clean - cluttered dicotomy is a useful but not absolute distinction to make.

Summary of Existing Analysis Techniques

Approximations commonly made in dynamic modeling involve the existence and placement of compliance: rigid models, lumped compliance or distributed compliance; structural shape approximations: beam equations or finite element approximations; and the use of higher order (nonlinear) terms. Time domain or frequency domain analysis may be used.

Rigid body equations of motion are nontrivial for six degree of freedom manipulators. The literature describes several computerized methods of obtaining these equations [5, 6]. Linearization of the problem for small motions results in tremendous simplification.

Lumped parameter analysis of practical manipulators is quite tractable for the linearized case [3]. Analysis for the Shuttle Remote Manipulator System (RMS) based on this approximation is proving useful in both man-in-the-loop and engineering simulations at NASA Johnson Space Center. [7, 8]. This approximation is straightforward when a relatively small number of masses and compliances are involved. A massless arm model of the RMS incorporating rigid orbiter and heavy payload is described with twenty four state variables (12 for the relative motion of payload and orbiter). Additional lumped masses would in general add twelve state variables each. "Cluttered" arms are poorly approximated with a massless arm. Compliance of drive trains may dominate skeletal compliance and thus justify the lumped mass approximation. The compliance matrix between masses is configuration dependent, and automated calculation is desirable as described in reference [3] and [4]. The effects of change of compliance with the joint variable can be incorporated by reevaluating the compliance as the state equations are integrated. Coriolis and other non-linear effects could also be included

Distributed parameter analysis recognizes that mass and compliance are both present in all structural material. The partial differential equations require an infinte number of state variables for exact solution. Hence true distributed parmeter analysis is (almost) never done but a truncated approximation is used. It is at this level of analysis that considerable difficulty and uncertainty arise. Type of truncation and number of modes (state variables) determines the accuracy of the model.

A common approximation to a distributed analysis involves a modal description of the shape into which a member will deform. These shapes for a particular beam, or shaft, or power transmission line are based on fixed, approximate boundary conditions on the member isolated from the system. The shapes constitute a set of orthogonal coordinates with which any motion of the member may be described. The dynamic equation describing the motion of the member in each mode or coordinate is decoupled from all other coordinates, but only when the boundary conditions are exact. Thus the usual procedure of selecting the lowest frequency mode shapes requires more approximate modes than are of interest to improve the accuracy of the low frequency modes which are of interest.

To describe a single beam in general motion for example, a minimum of two flexural modes one torsional mode and one compression mode is necessary. (In practice the compression mode might be omitted.) Two such beams separated by a massless joint would require a minimum of eight modes of flexible motion to find only the first flexible mode of the composite system. The true boundary conditions for a beam as determined by joint position and control algorithm and the other beam are not used in determining the mode shapes, thus the accuracy is always in question. One can be certain of sizeable error in the higher modes. In fact these modes would probably depend more on the second flexural mode of the separate beams than on, say the first compression mode.

Having decided on a modal description one can derive a model including non-linear effects if desired by Hamilton's principle or Lagrange's equations. The complexity of such a model of a six degree of freedom manipulator seems to be at the extreme upper limit of current numerical methods and digital computers. Such models have been attempted in conjunction with the RMS [9, 10]. The ratio of simulation time to real time on the order of 360 to one (2 hours for 20 seconds) have been observed on a CDC 6600. Even planar analysis for two links presents a large computational obstacle [2, 11]. This problem results from the wide separation between eigenvalues for the assumed modal shapes and the composite system, requiring small numerical integration step size, and from the tremendous complexity of the equations. Furthermore, the form of the equations is highly dependent on the kinematic configuration, and this author is aware of no automated equation generation capability applicable here.

Even if a designer is given equations of this complexity from a supreme diety one should consider their usefulness. Simulation runs are the only means of obtaining information on the system. The RMS without payload has structural frequencies of less than one cycle per second. With its maximum payload of 65,000 lb. twenty seconds will not allow one cycle of its lowest frequency. A possible use is in verifying a simpler model, if the designer could first verify the complex model and program. None the less the modal time domain model is capable of including all of the effects of flexibility and nonlinearity if the obstacles to its derrivation and use can be overcome.

An alternative to the all encompassing model described above is based on impedance methods. The beam in flexure is used as an example in the description of this method.

The bending of a beam in a plane is accurately described by a linear partial differential equation which is second order in time and fourth order in space. A solution may be expressed as a product of time and space functions. The time variable t is first transformed to a frequency variable ω. Herein arises the requirement that the system be linear. If one assumes all initial conditions are zero for the time function, the space function may be solved in terms of its arbitrary boundary conditions which may be a function of ω. This solution when expressed in transfer matrix form shows the linear dependence of the four boundary conditions at one end of the beam in terms of the other end. Two boundary conditions of the four on each end may be considered independent, and may be specified directly to be zero or some explicit function of ω. Explicit functions of ω may be forcing functions, and/or the solution to the differential equations of another component attached to the beam, and the boundary conditions on that component. This feature enables one to construct composite models of components attached to each other by multiplying the appropriate transfer matrices.

From this model one can obtain complex eigenvalues, a frequency response, or its inverse transform which is a time response, and true system mode shapes. The greatest disadvantage of this model is its restriction to mainly linear analysis. (Nonlinear stability analysis can be performed.) It does have some useful advantages over modal analysis. It is modular in form allowing modular verification and implementation. Furthermore, boundary conditions on structural members are represented exactly in as far as they are linear. The modal truncation is performed on the composite system. This allows accurate information on low frequency phenomena to be determined independently from high frequency information. If one system mode is desired a numerical search for that eigenvalue is performed. Additional modes are found with only a proportional increase in complexity. In as much as models are made up of standard elements, creating a new configuration involves only specifying the order of this occurance and their physical parameters.

Both the modal truncation method and impedance method are more difficult for cluttered arms. Finite element techniques can be used to obtain mode shapes for the modal method. Impedance methods have not been used (to this author's knowledge) with finite element methods for manipulator analysis but theoretically could be done. Frequency response would require evaluation of the transfer matrix of the finite element model (conceptually a lumped mass model) as a function of frequency. Determination of complex eigenvalues would require the transfer matrix evaluated in the complex plane. A convenient alternative is the use of several transfer matrices to represent a "semi-cluttered" arm member, a stepped beam for example. Experimental data can also be used with either technique, but is perhaps better documented for modal techniques.

Research Areas for Dynamic Models of Flexible Behavior

Several areas needing research will have been obvious to the reader from the preceeding. Outlined below are the author's suggestions.

I. Lumped Parameter Models

   A. Bounds on error for the lumped approximation

   B. Automatic generation of nonlinear equations

II. Distributed Parameter Models

   A. Modal truncation approximation

      1. Mode shapes for best accuracy

      2. Number of modes required for desired accuracy

      3. Bounds on error from modal truncation

      4. Boundary condition for finite element technique for best accuracy.

      5. Procedures for experimental determination of mode shapes.

      6. Bounds on nonlinear effects

      7. Numerical techniques for stiff systems

      8. Automated equation generation

   B. Impedance methods

      1. Approximate incorporation of nonlinearities such as Coriolis forces and change in configuration

      2. Improved search algorithms for complex poles

      3. Incorporation of the feedback of deflection in the joint control algorithm.

      4. Transfer matricies for tapered beams

      5. Describing function analysis techniques

      6. Control system design procedures with feedback of deflection

      7. Accuracy of linear approximation

III. Uses of Models in Research

   A. Guidelines for design optimization

   B. Improved control algorithms

   C. The potenial improvement in performance by trading brains (control) for brawn (structure and power).

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Manipulator Characteristics and Performance in Manipulation

As described above there are short comings in the ability to model certain dynamic behaviors. There are essentially no models of the way those dynamic behaviors affect the performance of the manipulation itself. The appendix is taken from reference [12] by the author and discusses this topic.